Improving Nitrogen Fertilizer Use Efficiency in Surface- and Overhead Sprinkler-Irrigated Cotton in the Desert Southwest

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Nitrogen fertilizer use efficiency (NUE) is low in surface-irrigated cotton (*Gossypium hirsutum* L.), especially when adding N to irrigation water. A NO_3 soil-test algorithm was compared with canopy reflectance-based N management with surface- overhead sprinkler-irrigation in central Arizona. The surface irrigation studies also compared fertigation of N fertilizer with knifing-in of N and the addition of a urease and nitrification inhibitor (Agrotain Plus, Koch Agronomic Services, Wichita, KS) to urea ammonium nitrate (UAN). Cotton lint and seed yields responded positively to N fertilizer in all four site-years. Recovery efficiency (RE) of N at low N fertilizer rates (60 to 76 kg N ha^{-1}) ranged from 21 to 61% with surface irrigation and from 81 to 97% with overhead sprinkler irrigation. Deep percolation below 1.8 m was 4 to 11% of applied surface irrigations and rain, but was undetectable in the overhead sprinkler. Leaching of NO_3 was apparently the largest N loss pathway in the surface-irrigated system. Fertigating UAN into surface irrigation resulted in similar lint yields and RE as knifing UAN. Use of Agrotain Plus with UAN gave similar yields and RE as using UAN alone. Reflectance-based N management using normalized difference vegetation index-amber (NDVIA) saved 50% of N fertilizer of the full soil-test based dose without a yield reduction in three of four site- years. Nitrogen fertilizer was over-prescribed with the soil-test-based treatment. This may have been due to not accounting for N mineralization, which the reflectance method indirectly measures.

Abbreviations: AE, agronomic efficiency; EFF, enhanced efficiency fertilizer; DCD, dicyandiamide; NDVIA, normalized difference vegetation index amber; NBPT, N-(n-butyl) thiophosphoric triamide; NUE, N use efficiency; RE, recovery efficiency; UAN, urea ammonium nitrate.

Core Ideas

- **Nitrogen use efficiency is low in surface-irrigated cotton.**
- **Canopy reflectance can guide in-season N management.**
- **Deep percolation of rain and irrigation is associated with nitrate leaching.**

Level land and canal infrastructure means that level-basin surface irrigation in raised beds is the predominant irrigation system for cotton production in central Arizona. High yields (i.e., statewide averages 1700 kg lint ha^{-1} [USDA–NASS, 2015]) are achieved with typical 100 cm or more in-season surface irrigation. Nitrogen requirements of the plant are assumed to be high for these high yields. Nitrogen fertilizer is usually managed with early season ground applications followed by “fertigations” i.e., dribbling liquid UAN into the canal. Surface-run fertigation has the advantage of being applicable later in the season than knifing with a ground applicator, and with lower costs. However, with typical surface irrigations in the range of 10 to 15 cm, there is potential for deep leaching of N fertilizer when it is fertigated. Even with ground-applied N, leaching losses in the western United States with surface and/or furrow irrigations have been reported to be substantial (Jaynes et al., 1992; Silvertooth et al., 1992; Rice et al., 2001). Additionally, there is concern about the uniformity of N fertigations with surface irrigation (Adamsen et al., 2005; Perea et al., 2011; Playan and Faci, 1997). There

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is little research, however, that compares ground applications of N fertilizer with fertigations in these systems.

The use of nitrification and/or urease inhibitors with UAN to improve NUE has been well-researched with cereal crops (Blackmer and Sanchez, 1988; Randall et al., 2003; Halvorson and Del Grosso, 2013; Dell et al., 2014; Hatfield and Parkin, 2014). Fewer such studies have been conducted with cotton (Freney et al., 1993; Kawakami et al., 2012; Watts et al., 2014). Many studies with crops other than cotton have shown that enhanced efficiency fertilizers (EFF) have potential to reduce NO_3 leaching losses and N_2O emissions (Motavalli et al., 2008; Sanz-Cobena et al., 2012; Maharjan et al., 2014; Halvorson et al., 2014). A well-tested EFF is Agrotain Plus, which consists of the urease inhibitors N-(n-butyl) thiophosphoric triamide (NBPT), and the nitrification inhibitor, dicyandiamide (DCD) (Mention of specific products or manufacturers does not constitute endorsement by the USDA).

In the last 5 yr, overhead sprinklers systems have been installed in farmland of central Arizona at an increasing rate. Drought in the lower Colorado River Basin has been a fact of life since 2000 (Scanlon et al., 2016). Overhead sprinkler installation is in response to the drought, and the hope that water use efficiency will be greater than with surface irrigation. However, very little N fertilizer management research has been conducted in the US Southwest with crops like cotton under overhead sprinklers. Bronson et al. (2011) reported that in Texas, NUE in cotton is greater with overhead sprinklers than with surface irrigation, but similar comparisons are lacking for the US desert Southwest.

Nitrogen fertilizer management for cotton in the western United States usually begins with a 0- to 60- to 0- to 100-cm depth preplant soil NO_3 test and a 1-kg N internal plant N requirement per 10 kg lint (Zelinski, 1985; Zhang et al., 1998; Chua et al., 2003; Hutmacher et al., 2004; Bronson et al., 2011; Main et al., 2013). In addition to the often substantial preplant soil NO_3 credit, irrigation water credits can be included as well (Bronson et al., 2009). Nitrogen management recommendations for cotton in Arizona and California have not been updated in >20 yr (Doerge et al., 1991; Weir et al., 1996). The emphasis for Arizona has been on the use of petiole-NO_3 sampling to guide N fertilizer applications in cotton (Silvertooth et al., 2011). In California, the combined use of preplant soil profile NO_3 and in-season petiole sampling is recommended (Hutmacher et al., 2004; Weir et al., 1996). However, petiole sampling is laborious, laboratory turn-around can be an issue, and results can be variable (Bronson et al., 2001).

There has been much interest in the last 10 yr on the use of "active optical sensors" to guide N fertilization in crops, including cotton (Bronson et al., 2003; Chua et al., 2003; Bronson et al., 2011; Oliveira et al., 2012; Raper et al., 2013). Typically canopy reflectance is measured in visible and in near infrared wavelengths, and a vegetation index such as the normalized difference vegetation index (NDVI) (Tucker, 1979) is calculated. In subsurface drip-irrigated cotton in West Texas, NDVI-based N fertilizer management allowed reducing N rates without hurting lint yields (Yabaji et al., 2009; Bronson et al., 2011). Little canopy reflectance-guided N management research has been done in the Southwestern United States. The preplant soil profile NO_3 test has been shown to be valuable to cotton N management in West Texas (Booker et. al., 2007; Bronson et al., 2001; Bronson et al., 2009) and California (Hutmacher et al., 2004), but this has not been tested in Arizona. The goal of this study was to understand how N management strategies affect NUE of irrigated cotton in a highly productive arid environment for two irrigation systems.

The objectives of this study were to:

1. Compare lint and seed yields, N uptake, and NUE with fertigation of UAN with ground, knife applications of UAN for a surface-irrigated field, furrowed for cotton.
2. Compare lint and seed yields, N uptake, and NUE with fertigation of UAN with fertigation of ammonium sulfate and with fertigation of UAN with Agrotain Plus (nitrification and urease inhibitor) for a surface-irrigated and overhead sprinkler-irrigated field.
3. Compare lint and seed yields, N uptake, and NUE with soil-test-based N fertilizer management with canopy reflectance-based N management in a surface-irrigated and overhead sprinkler-irrigated field.

MATERIALS AND METHODS

Cotton field studies were conducted at the Maricopa Agricultural Center near Maricopa, AZ (33.067° N, 111.97° W and 360 m above sea level) from 2012 to 2015. The soil is a Trix sandy clay loam (fine-loamy, mixed, superactive, calcareous, hyperthermic Typic Torrifluvent). The top 30 cm of soil was of pH 7.8 and was low soil in organic matter, with total N and C of 0.5, and 5.0, g kg^{-1}, respectively. Soil extractable K and P levels were high, that is, >300, and 100 mg kg^{-1}, respectively. All sites were fallow for 2 yr. The surface irrigation study area in 2012 and 2013 consisted of 18, eight-row plots that were 164 m long. Six N fertilizer management treatments were imposed on the surface-irrigated field, arranged as three randomized complete blocks each year. The overhead sprinkler study was conducted in 2014 and 2015 under one 54-m × 170-m span of a 6-span Zimmatic (Lindsay Corp., Omaha, NE) linear-move overhead sprinkler, 500 m from the surface-irrigated field and on the same Trix sandy clay loam soil. Under the sprinkler system, eight N fertilizer treatments were assigned to eight, six-row plots that were 36 m long. The sprinkler study was arranged in four randomized complete blocks arrayed north to south, with each replicate separated by 3 m of planted buffer. Cotton cultivar 'Delta Pine 1044 B2RF' (Monsanto Co., St, Louis, MO) was planted on 1-m wide raised beds at the rate of 15 kg ha^{-1} on 23 Apr. 2012, 1 May 2013, 1 May 2014, and 29 Apr. 2015. In each site-year, soil was sampled to 180 cm (in 30-cm increments) for NO_3–N analysis (Adamsen et al., 1985) at the start of the season, and after harvest using a Giddings soil sampling machine (Giddings Machine Co., Ft. Collins, CO). Soil sampling was done at four GPS-referenced points per plot in the 164-m long surface irrigation plots, and at two GPS-referenced points per plot in the 36-m long sprinkler

Table 1. Water balances for N management studies in surface-irrigated and overhead sprinkler-irrigated 'DP 1044 B2RF' cotton, Maricopa, AZ, in 2012 to 2015.

Year	Irrigation system	ET†	Rain	Irrigation	Change soil storage in 0–1.8 m	Deep percolation	Portion of irrigation and rain going to deep percolation
		cm					%
2012	Surface	–81.6	9.5	76.3	–5.1	9.4	11.0
2013	Surface	–76.6	1.3	73.7	–4.7	3.2	4.3
2014	Sprinkler	–86.7	8.5	72.0	–5.7	0	0
2015	Sprinkler	–96.4	3.8	78.4	–7.3	0	0

† ET, evapotranspiration; 112, 101, 91, and 118 d were used in 2012, 2013, 2014, and 2015, respectively.

irrigation plots. A bulk density of soil of 1.6 g cm^{-3} was used to convert NO_3–N concentrations from mg kg^{-1} to kg ha^{-1}.

Preplant irrigations of 23 and 15 cm were applied in March for the surface and sprinkler-irrigated fields, respectively. Irrigation was applied every 10 to 14 d starting at first square under surface irrigation. Sprinkler irrigation was applied with spray nozzles for 4 d after planting, and then every 3 to 4 d after first square with drop hoses that dragged in the middle of each furrow (Thorp et al., 2017). In both studies, irrigation scheduling decisions were based on the depletion of total available water over the crop root zone depth (Martin and Gilley, 1993). Available soil water was obtained by a daily soil water balance model over the cotton root zone (Hunsaker et al., 2005) that included estimated daily crop evapotranspiration (ET_c) by the FAO-56 dual crop coefficient procedures (Allen et al., 1998):

$$ET_c = (K_{cb} \times K_s + K_e) ET_o \qquad [1]$$

where ET_c is in mm, K_{cb} is the basal crop coefficient, K_s is the water stress coefficient, K_e is the soil evaporation coefficient, and ET_o is grass reference evapotranspiration in mm. Daily ET_o and meteorological data were provided by a University of Arizona, Meteorological Network (AzMet; www.ag.arizona.edu/azmet) weather station located about 2 km from the field. The K_{cb} curve used in Eq. [1] for cotton was modified for local conditions and is reported in Hunsaker et al. (2005). Depletion of total available water for a maximum cotton root zone of 1.8 m (Hunsaker et al., 2005; Allen et al., 1998) was allowed to 45% for both the surface and sprinkler studies. Irrigation efficiencies of 90 and 95% were incorporated into the irrigation calculations for surface and overhead sprinkler, respectively. The surface and sprinkler fields were each laser-graded prior to the studies, which is a common practice in the area and helps improve the distribution of irrigation water application. Surface irrigation water was applied to the three replicates of each N fertilizer treatment at the same time, and water amounts were measured with an in-line propeller flowmeter. Blocked ends for each plot in the surface-irrigated field ensured that all water applied to a plot infiltrated within the plot (i.e., there was no runoff). Irrigation amounts in the sprinkler study were recorded by an in-line flowmeter and an on-board data logger. Runoff of irrigation water to plots under sprinkler was assumed to be negligible, as confirmed by visual observation. Seasonal irrigation amounts, excluding the preplant irrigations, were 76, 74, 72, and 78 cm for 2012, 2013, 2014, and 2015, respectively (Table 1). When rain is added to seasonal irrigation, the percentage ET_c replacement was 105 and 98% for surface irrigation in 2012 and 2013, respectively, and 93 and 85% with overhead sprinkler irrigation in 2014 and 2015, respectively (Table 1).

Nitrogen treatments are described in Table 2 and Table 3. Zero-N control plots were established for all site-years. The algorithm used for the soil-test based N rate was based on Bronson et al. (2011) for irrigated cotton in Texas. We modified the recommendation to use soil profile NO_3 to a depth of 90 cm, compared to the 60-cm test used for deficit-irrigated, short-season cotton in Texas. The cotton lint expected yield for this study in the surface irrigation was 1960 kg ha^{-1}, and a 196 kg N ha^{-1} N rate was used, compared to a 1400 kg lint goal ha^{-1} and 140 kg N requirement ha^{-1} for Bronson et al. (2011). In the overhead sprinkler field, we raised the expected lint yield to 2240 kg ha^{-1}, and used an N rate of 224 kg N ha^{-1}. Nitrogen fertilizer was applied as UAN solution (320 g N kg^{-1}), except for the first year in the surface irrigation, when the ammonium sulfate treatment was applied as a 200 g N kg^{-1} solution. Liquid N fertilizers were applied by either knifing-in the side of the bed (25 cm off seed row and

Table 2. Nitrogen fertilizer treatments for surface-irrigated cotton, Maricopa, AZ, in 2012 to 2013.

Treatment number	Nitrogen treatment	Fertilization mode	Fertilizer source
1	Zero-N	None	None
2	Soil-test based N†	Knife	Urea ammonium nitrate
3	Soil-test based N†	Fertigate	Urea ammonium nitrate
4	Soil-test based N†	Fertigate	Ammonium sulfate or urea ammonium nitrate with addition of Agrotain Plus
5	Reflectance-based N‡	Knife	Urea ammonium nitrate
6	Reflectance-based N§	Fertigate	Urea ammonium nitrate

† Based on lint yield goal of 1960 kg ha^{-1}, and a 196 kg N ha^{-1} N requirement, minus 0–90 cm soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 1-m irrigation of 2 mg L^{-1} NO_3–N water).

‡ First split application equals 50% Treatment no. 2; second split application based on NDVIA relative to Treatment no. 2.

§ First fertigation 50% Treatment no. 3; second fertigation based on NDVIA relative to Treatment no. 3.

Table 3. Nitrogen fertilizer treatments for overhead sprinkler-irrigated cotton, Maricopa, AZ, in 2014 to 2015.

Treatment number	Nitrogen treatment	Fertilizer source
1	Zero-N	None
2	Soil-test based N†	Urea ammonium nitrate
3	1.3 × Soil-test based N†	Urea ammonium nitrate
4	Soil-test based N†	Urea ammonium nitrate with addition of Agrotain Plus
5	Reflectance-based N-1‡	Urea ammonium nitrate
6	Reflectance-based N-2§	Urea ammonium nitrate
7	Reflectance-based N-1‡	Urea ammonium nitrate with addition of Agrotain Plus
8	Reflectance-based N-2§	Urea ammonium nitrate with addition of Agrotain Plus

† Based on lint yield goal of 2240 kg ha^{-1}, and a 224 kg N ha^{-1} N requirement, minus 0– 90 cm. soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 1 m irrigation of 2 mg L^{-1} NO_3–N water).

‡ First split application equals 50% Treatment no. 2; second and third split application based on NDVIA relative to Treatment no. 2.

§ First split application equals 50% Treatment no. 3; second and third split application based on NDVIA relative to Treatment no. 3.

10 cm deep) or injecting into the surface irrigation header line. Fertigations were done with a 110 L h^{-1} diaphragm pump for the three replicates of each N fertigation treatment at a time (with supply gates closed for the other treatments). For surface irrigation, N was applied in two equal splits, at first square and at first bloom. Crop height at mid bloom prevented ground applicators from being used to knife-in N in the surface irrigation study. For the overhead sprinkler system, N was split into three applications, first square, first bloom, and mid bloom. A high clearance, self-propelled tractor (Hamby Inc., Lubbock, TX) was used to apply N under the sprinkler, just prior to an irrigation. It used variable-rate Turbodrop Variable Rate fertilizer nozzles (Greenleaf Technologies, Covington, LA) on drops at 1-m horizontal spacing, and with a Raven SCS 440 controller (Raven Industries, Sioux Falls, SD), Raven butterfly valve, Raven GPS, and flow meter (Mon et al., 2016). Agrotain Plus was added to UAN at the rate of 0.8% by weight for 2013 to 2015. Nitrogen application rates of UAN with Agrotain Plus were adjusted to account for the N concentrations of DCD and NBPT.

Canopy reflectance was measured 10 to 12 times during the growing season all 4 yr using Crop Circle ACS-470 active sensors (Holland Scientific Inc., Lincoln, NE). The Crop Circle sensor has a 30° x 14° field of view and was positioned 1 m above the canopy of the tallest plants. Sensors were mounted on a four-wheel cart (White and Conley, 2013) on the surface-irrigated field and on the front end of the Hamby high-clearance tractor in the overhead sprinkler field. The rate of data acquisition was 5 Hz, and one pass per 164 m plot was made over row four (of eight) on the surface-irrigated field at 0.6 m s^{-1}. Crop Circle sensors were passed over row three (of six) of each plot in the sprinkler field. Reflectance was measured with tandem Crop Circle ACS-470 sensors (two mounted end-to-end over the same row with 30 cm separation between light sources) allowing six band-pass interference filters: 530, 590, 670, 730, 780, and 800 nm in 2012 and 2013. In 2014 and 2015, the 780 nm filter was replaced with a 550-nm filter.

The vegetation index NDVI-Amber (NDVIA) (Solari et al., 2008; Bronson et al., 2011) was used for the reflectance-based N treatment and was calculated as:

$$(R_{800} - R_{590})/(R_{800} + R_{590})$$

The NDVIA was chosen instead of NDVI using red reflectance because previous studies showed that NDVIA is slightly more sensitive to N deficiency than NDVI (red) (Bronson et al., 2011; Bronson et al., 2017).

The N rate for the reflectance-based N treatment was initially set at 50% of the soil-test treatments. When NDVIA in the reflectance-based N plots fell statistically below ($P < 0.05$) NDVIA in the soil-test plots, then the N rate was increased to match the soil-test plots (Tables 2 and 3; Bronson et al., 2011). This feedback approach assesses when the reflectance-based plants are deficient in N, and when the initial low N fertilizer rate needs to be increased.

Galvanized steel neutron probe access tubes were installed 1 to 2 wk after emergence at four locations along nine of the 18 plots in the surface irrigation study. The access tubes were installed within all three plot replicates for three treatments (the zero-N, soil-test-based knife, and soil-test-based fertigation) for a total of 36 georeferenced tube locations. In the overhead sprinkler studies, one access tube was installed in each plot. Beginning in mid-May of each year, weekly volumetric soil water contents were measured from 10 to 190 cm in 20-cm increments at all access tube locations using field-calibrated neutron probes (Model 503, Campbell Pacific Nuclear, CPN, Martinez, CA). The soil water contents between two probe measurement dates were used to determine the change in soil water storage over an effective cotton root depth of 180 cm for each of the three N treatments.

Cotton was picked in early November of each year with two pickers, a Case 1822, and a Case 2155 (Case IH, Grand Island, NE). The Case 1822 was a two-row picker and was used to pick rows four and five of each plot of the surface-irrigated field and rows three and four in the sprinkler field. Weights were taken on 6 m lengths centered on the GPS-referenced points. Each of these samples was ginned and seed and lint percentages were determined. The Case 2155 was a 4-row picker that was equipped with AgLeader optical yield monitor sensors for rows 1 and 4 Ag Leader, Ames, IA). Yield maps were made of rows three and six of each surface-irrigated plot and of rows two and five of each sprinkler-irrigated plot. Lint turnout from the 6-m samples was applied to the yield map using a spatial join operation in ArcMap 10 (ESRI, 2015).

Biomass and total N uptake was determined on plants sampled on 50 cm from two rows at first open boll (early August) at each of the 72 GPS-referenced points in the surface-irrigated field and at the 64 GPS-referenced points in the sprinkler field.

Table 4. Pre-plant and post-harvest soil NO_3–N as affected by N management in surface-irrigated cotton, Maricopa, AZ, in 2012 to 2013.

			Sampling date						
			March 2012		March 2013		December 2013		
					Soil depth, cm				
Nitrogen treatment	Fertilizer source†		0–180	0–90	0–180	0–90	0–180	0–90	150–180
			kg NO_3–N ha^{-1}						
Zero-N			92	26	82	50	50	33	2.5
Soil-test based N	Knife	UAN	81	27	178	52	152	82	34
Soil-test based N	Fertigate	UAN	58	28	184	58	213	92	74
Soil-test based N	Fertigate	AS or UAN with addition of Agrotain Plus	73	30	116	52	113	69	25
Reflectance-based N	Knife	UAN	36	23	59	38	36	29	1.9
Reflectance-based N	Fertigate	UAN	57	26	71	38	59	38	14
Standard error			40	9	60	12	80	19	41
		Single degree of freedom contrasts							
Knife vs. fertigate			NS‡	NS	NS	NS	NS	NS	NS
UAN vs. UAN with Agrotain Plus			NS	NS	NS	NS	NS	NS	NS
Reflectance. vs. soil test			NS	NS	*	*	*	**	NS
N-fertilized vs. zero-N			NS	NS	NS	NS	NS	NS	NS

* Significant at $P < 0.05$; ** significant at $P < 0.01$.

† UAN, urea ammonium nitrate; AS, ammonium sulfate.

‡ NS, no significance at $P < 0.05$.

Nitrogen content was analyzed on stems, leaves, burrs and seed on a Leco Truspec CN Analyzer (Leco Corp, St. Joseph, MN). Fertilizer N recovery efficiency, physiological N use efficiency and agronomic use efficiency (using lint instead of grain) were calculated (Dilz, 1988; Isfan, 1990; Novoa and Loomis, 1981; Bronson, 2008).

Deep percolation of irrigation water was estimated by water balances in the 0- to 180-cm soil depth calculated for every time period between neutron probe soil moisture measurement dates according to Maharjan et al. (2014) as:

$$D = (P + I - ET) + \Delta S$$

where D is drainage, P is precipitation, I is irrigation, and ΔS is weekly change in soil water storage. If profile soil moisture differed by N treatments, then separate water balances were constructed. The maximum cotton root zone was assumed to be 1.8 m (Erie et al., 1982; Hons and McMichael, 1986; Farahani et al., 2009), and water surplus in the water balance was declared leached below that depth.

To estimate seasonal deep drainage, cumulative drainage was calculated from the weekly water balances. If the cumulative, seasonal estimate of drainage was negative, then deep percolation was considered to be zero (Table 1).

ArcMap 10 was used to intersect 4-m long lengths of GPS-located-canopy reflectance data points with geo-positioned plot polygons, and to similarly process plot length yield map data (ESRI, 2015). PROC MIXED (SAS Institute, 2013) was used to test the N fertilizer treatment and year effects for NDVIA, lint and seed yield, first open boll biomass, N uptake, IUE, AE, RE, and soil NO_3–N. Replicate was considered random, and N treatment and year was considered fixed.

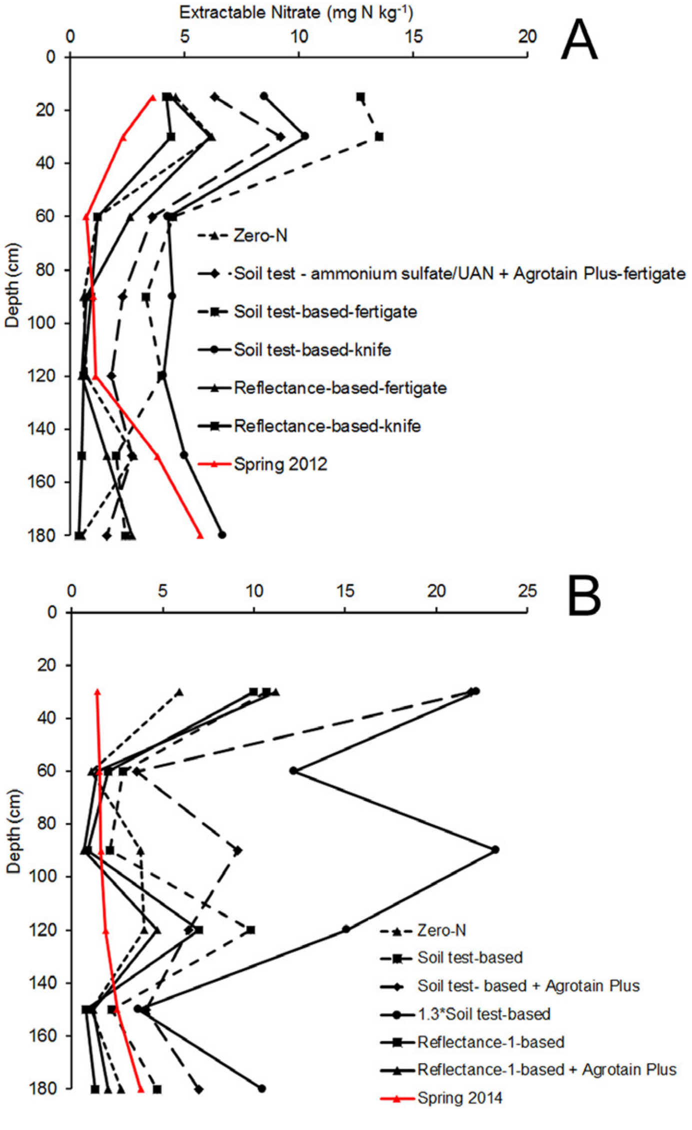

Fig. 1. Post-harvest soil profile NO_3–N as affected by 2-yr N fertilizer management in surface-and overhead sprinkler-irrigated cotton, Maricopa, AZ; (A) November, 2013, Surface irrigation; and (B) November, 2015, Overhead sprinkler irrigation.

RESULTS AND DISCUSSION

Surface Irrigation in 2012

Initial soil NO_3–N in early May 2012 was low in this study, with an average of 26 kg NO_3–N ha^{-1} in the 0- to 90-cm profile (Table 4; Fig. 1A). Nitrogen fertilizer applied was 148 kg N ha^{-1} on the soil-test-based N management treatments and 74 kg N ha^{-1} on the reflectance-based treatments. Rates were not increased in the reflectance plots because NDVIA never differed between those plots and the soil-test-based N plots ($P <$ 0.05, Fig. 2A). Lint and seed yields were similar among all of the N-fertilized treatments, but significantly greater than the zero-N plots ($P < 0.05$, Table 5). Lint yield averaged 1864 kg ha^{-1} in the N-fertilized plots (1889 kg ha^{-1} with yield map data), slightly less than the 1960 kg ha^{-1} yield expected yield. Total N uptake at first open boll was positively affected by N fertilizer, but was not affected by N source. Zero-N cotton plots had total N uptake of a remarkable 130 kg N ha^{-1} (Table 5). When we subtract from this value 26 kg N ha^{-1} of soil profile NO_3–N and 22 kg N ha^{-1} of calculated irrigation water NO_3 (106 cm of preplant and in-season irrigation with 2 mg L^{-1} NO_3–N), the estimated net N mineralization is 82 kg N ha^{-1}. Recovery efficiency of N fertilizer was not affected by N treatment and ranged from 21 to 29% (Table 5). This is similar to values for furrow-irrigated cotton in West Texas (Bronson, 2008).

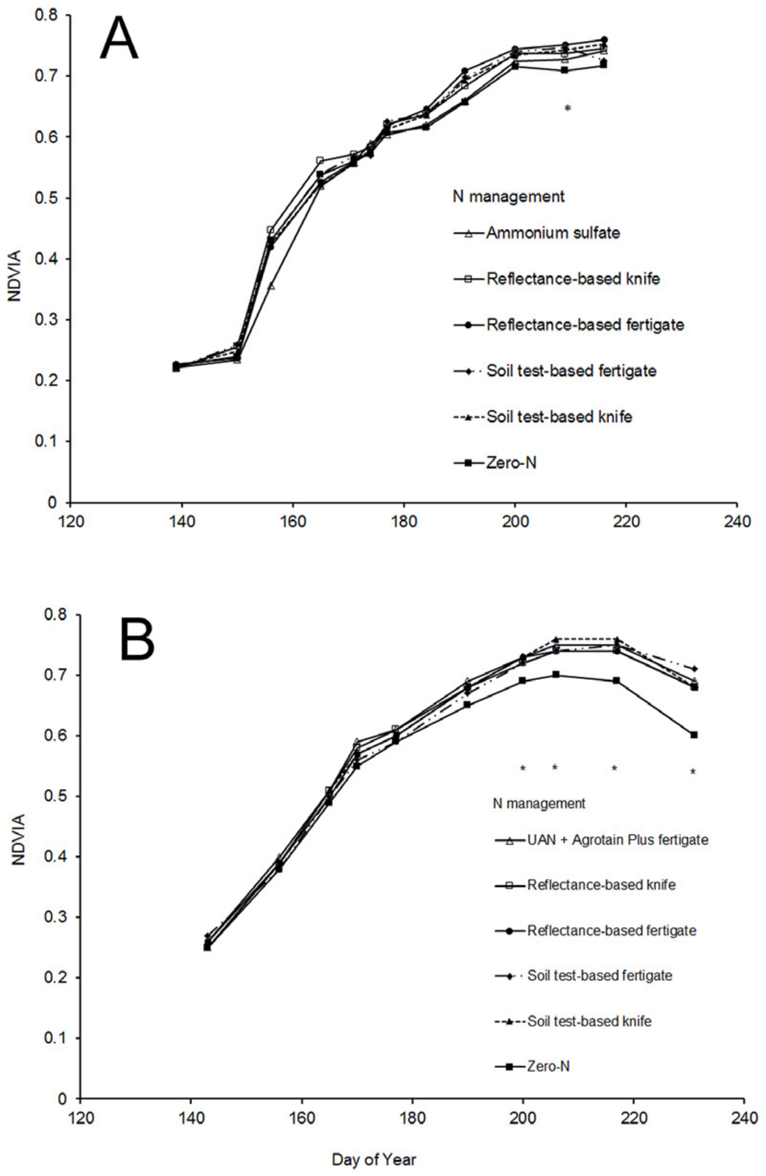

Fig. 2. Normalized difference vegetation index-amber (NDVIA) as affected by N-fertilizer management in surface-irrigated cotton, Maricopa, AZ in (A) 2012, and (B) 2013 (* indicates N-fertilized plots are significantly less than the zero-N plots at $P < 0.05$).

Internal N use efficiency ranged from 10.6 to 14.9 kg lint kg plant-N (Table 5), with the highest values on the 74 kg N ha^{-1} N rates for reflectance treatments. These values are similar to previous reports in West Texas (Bronson, 2008) but much higher than the 5 kg lint kg plant-N reported previously in Arizona (Navarro et al., 1997).

Table 1 shows the soil water balance components for 0- to 180-cm root depth for each season, as previously described. For 2012, estimated ET$_c$ over the investigated period (Table 1) was about 82 cm, while the portion of the rain and irrigation inputs going to deep percolation was about 11%. Deep leaching occurred in five of the eight irrigations and net depletion occurred in the other three irrigations (data not shown).

Surface Irrigation in 2013

Pre-fertilization soil NO_3 was greater in 2013 than in 2012, with an average of 55 kg NO_3–N ha^{-1} in the 0- to 90-cm profile of the soil-test based-N plots ($P < 0.05$, Table 4). Nitrogen fertilizer applied was 119 kg N ha^{-1} on the soil-test based N management treatments and 60 kg N ha^{-1} on the reflectance-based treatments. Similar to 2012, N rates were not increased on the reflectance plots because NDVIA did not differ between those plots and the soil-test-based N plots (Fig. 2B). Biomass at first open boll was greater than in 2012 ($P < 0.05$, Table 5). Total N uptake at first open boll was positively affected by N fertilizer, but was not affected by N source. Nitrogen uptake was similar to 2012 ($P > 0.05$). Nitrogen uptake with zero-N was a robust 122 kg N ha^{-1} (Table 5). When we subtract from this value 50 kg N ha^{-1} of initial soil profile NO_3–N in the zero-N plots, and 21 kg N ha^{-1} of calculated irrigation water NO_3 (104 cm of 2 mg L^{-1} NO_3–N), the estimated net N mineralization is 51 kg N ha^{-1}. Recovery efficiency of N fertilizer was not affected by N treatment and ranged from 35 to 61% ($P > 0.05$, Table 5). These values are greater than in 2012 and for furrow-irrigated cotton in West Texas (Bronson, 2008), due in part to the slightly lower N fertilizer rates used in 2013. Lint and seed yields were similar among all of the N-fertilized treatments, but significantly greater than the zero-N plots ($P < 0.05$, Table 5). Lint yield averaged 1937 and 1912 kg ha^{-1} for the 6-m data and yield mapped harvest data, respectively, similar to the 1960 kg ha^{-1} yield goal.

Internal N use efficiency averaged ranged from 10.6 to 13. 9 kg lint kg N (Table 5), with the highest values again being with the lower N rates of the reflectance treatments. The NDVIA did not show differences among the N-fertilized plots ($P < 0.05$, Fig. 2B). Nitrogen deficiency did not appear until 200 d of year (July 19) at peak bloom in the NDVIA data.

Deep percolation of rain and surface irrigation in 2013 was 4% while ET_c was 77 cm (Table 1). Similar to 2012, deep leaching occurred in five of the eight irrigations (data not shown). Leaching of NO_3–N below 1 m was observed after two seasons, especially in the soil-test knife treatment, which had high concentrations throughout the soil profile (Fig. 1A). There was significantly greater soil NO_3 in the 90- to 180-cm layers in November of 2013 with both soil test treatments compared to the reflectance treatments, and less than the original spring, 2012 concentrations ($P < 0.05$, Fig. 1A).

Post-harvest residual soil profile NO_3 was greater with soil-test-based N treatments (knifed and fertigated) compared to the reflectance-based N treatments ($P < 0.05$, Table 4; Fig. 1A). Nitrate-N in the deepest layer sampled (150–180 cm) was statistically similar among N treatments, with large variation ($P > 0.05$).

Overhead Sprinkler-Irrigation in 2014

Pre-fertilization soil NO_3–N averaged 23 kg NO_3–N ha^{-1} in the 0- to 90-cm profile (Table 6, Fig. 1B). The soil-test based N applications were 179 kg N ha^{-1}.

The NDVIA in the two reflectance-based treatments never fell below their respective references during the growing season ($P < 0.05$, Fig. 3A). Therefore the two NDVI-based N treatments were not adjusted upward. In fact, NDVIA with zero-N did not drop significantly below the N-fertilized treatments until the 217th day of the year (3 August) or peak bloom. This was 1 mo after the third and final split of N fertilizer.

Biomass at first open boll averaged 9.1 Mg ha^{-1}, with no effect of N treatment. Total N uptake at first open boll with N fertilizer averaged 194 kg N ha^{-1}, which was significantly greater than the 146 kg N ha^{-1} with zero-N ($P < 0.05$, Table 7). Net N mineralization was estimated at 105 kg N ha^{-1} (146 kg N ha^{-1} N uptake – 18 kg NO_3–N ha^{-1} in irrigation – 23 kg NO_3–N ha^{-1}

Table 5. Lint yield, seed yield, seed N uptake, internal and agronomic N use efficiency, biomass, N uptake, and N recovery efficiency as affected by N management in surface-irrigated cotton, Maricopa, AZ, in 2012 to 2013.

Nitrogen treatment	Fertilization mode	Fertilizer source†	Fertilizer rate	Lint yield– 328 m^2	Lint yield– 48 m^2	Seed yield	Seed N uptake	Internal N use efficiency	Agronomic N use efficiency	Biomass	Total N uptake	N Recovery efficiency
			kg N ha^{-1}	—— kg ha^{-1} ——			kg N ha^{-1}	— kg lint kg N^{-1} —		Mg ha^{-1}	kg N ha^{-1}	%
					2012							
Zero-N			0	1662	1624	2426	95	12.8	–	7.3	130	–
Soil-test based N	Knife	UAN	148	1929	1924	2916	124	11.8	2.0	7.9	167	27
Soil-test based N	Fertigate	UAN	148	1926	1818	2751	114	11.1	1.4	8.3	165	23
Soil-test based N	Fertigate	AS	148	1802	1786	2684	108	10.6	1.8	8.9	173	29
Reflectance-based N	Knife	UAN	74	1935	1920	2858	111	14.9	4.0	6.8	132	21
Reflectance-based N	Fertigate	UAN	74	1855	1872	2743	106	13.6	3.5	7.8	141	26
Standard error				80	123	137	4.0	1.1	0.8	0.5	11	9.0
					Single degree of freedom contrasts							
Knife vs. fertigate				NS‡	NS	NS	**	NS	NS	NS	NS	NS
Ammonium sulfate. vs. UAN				NS	NS	NS	NS	NS	NS	NS	NS	NS
Refl. vs. soil test				NS	NS	NS	NS	**	*	*	**	NS
N-fertilized vs. zero-N				**	*	*	**	NS	NS	NS	*	NS
					2013							
Zero-N			0	1638	1601	2020	78	13.8	–	8.2	122	–
Soil test-based N	Knife	UAN	119	1900	1846	2446	109	10.6	2.1	9.1	175	44
Soil test-based N	Fertigate	UAN	119	1805	1925	2524	107	12.1	2.7	8.9	159	37
Soil test-based N	Fertigate	UAN with Agrotain Plus	119	1989	1933	2487	102	12.4	2.8	9.7	159	35
Reflectance-based N	Knife	UAN	60	1951	1971	2529	99	12.6	6.2	9.8	160	61
Reflectance-based N	Fertigate	UAN	60	1917	2012	2541	95	13.9	6.9	9.6	147	42
Standard error				132	164	201	8.9	0.8	1.7	0.9	12	17
					Single degree of freedom contrasts							
Knife vs. fertigate				NS	NS	NS	NS	*	NS	NS	NS	NS
UAN vs. UAN + Agro				NS	NS	NS	NS	NS	NS	NS	NS	NS
Reflectance-based N vs. soil test				NS	NS	NS	NS	*	**	NS	NS	NS
N-fertilized vs. zero-N				*	*	*	**	*		*	**	NS

* Significant at $P < 0.05$.

** significant at $P < 0.01$.

† UAN, urea ammonium nitrate; AS, ammonium sulfate.

‡ NS, no significance at $P < 0.05$.

Table 6. Pre-plant and post-harvest soil NO_3–N as affected by N management in overhead sprinkler-irrigated cotton, Maricopa, AZ, in 2014 to 2015.

		Sampling date									
		March 2014		November 2014			March 2015		December 2015		
		Soil depth, cm									
Nitrogen treatment	**Fertilizer source†**	**0–180**	**0–90**	**0–180**	**0–90**	**60–72**	**0–180**	**0–90**	**0–180**	**0–90**	**150–180**
		kg NO_3–N ha^{-1}									
Zero-N		66	22	56	34	1.7	66	47	100	48	3.0
Soil test-based N	UAN	44	19	127	80	3.2	122	71	142	69	5.3
1.3×Soil test-based N	UAN	60	24	222	165	4.0	327	236	365	245	12
Soil test-based N	UAN with Agrotain Plus	48	19	153	106	3.7	246	166	225	155	7.8
Reflectance-based N-1	UAN	32	17	46	28	1.7	64	49	90	48	2.2
Reflectance-based N-2	UAN	74	23	96	55	2.6	152	102	113	56	4.6
Reflectance-based N-1	UAN with Agrotain Plus	57	23	58	35	1.7	88	63	94	59	2.2
Reflectance-based N-2	UAN with Agrotain Plus	53	19	67	38	2.8	124	78	148	56	8.4
Standard error		18	4.6	40	32	1.5	81	59	71	55	4.0
		Single degree of freedom contrasts									
UAN vs. UAN + Agrotain Plus		NS‡	NS	NS	NS	NS	NS	NS	NS	NS	NS
Reflectance-based N-1 vs. soil test		NS	NS	**	**	NS	NS	NS	**	**	NS
1.3×Soil test vs. soil test		NS	NS	*	*	NS	*	*	**	**	NS
N-fertilized vs. zero-N		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at $P < 0.05$; ** significant at $P < 0.01$.

† UAN, urea ammonium nitrate; AS, ammonium sulfate.

‡ NS, no significance at $P < 0.05$.

in 0- to 90-cm soil [Table 6]). Recovery efficiency of added N fertilizer was numerically greater than in the 2012 surface irrigation study but was similar to that of the 2013 study ($P > 0.05$). It should be emphasized that the 2013 study had lower N fertilizer application rates than in 2014, therefore higher RE would be expected (Torbert and Reeves, 1994; Norton and Silvertooth, 2007). The greatest RE in 2014 was with the low N rate of 90 kg N ha^{-1} with the reflectance strategy-1 treatments where RE was 50 to 55% (Table 7). The lowest RE of 24% was with the 1.3 × soil-test rate (233 kg N ha^{-1}) and surprisingly, with soil-test rate (179 kg N ha^{-1}) with Agrotain Plus (Table 7). Internal N use efficiency in 2014 for N-fertilized plots averaged 9.4 kg lint kg plant-N ha^{-1}, with no effect of N treatment ($P > 0.05$, Table 7). Lint yields showed significantly lower values ($P < 0.05$) zero-N plots (1694 and 1725 kg lint ha^{-1} for whole plot yield and 6-m data) vs. the average of the N-fertilized plots (1842 and 1818 kg lint ha^{-1}). These yield levels were substantially lower than the 2240 kg ha^{-1} yield goal.

The use of Agrotain Plus had no effect on biomass, N uptake, RE, AE or lint yields ($P > 0.05$, Table 5). Nitrogen uptake numerically was greater than in the surface irrigation studies, but biomass levels were similar.

Deep percolation of rain and irrigation was estimated to be zero under the sprinkler in 2014 (Table 1). Soil NO_3 after harvest showed substantial build-up in the 1.3 × soil-test treatment, compared with soil-test (Table 6). Similar to the surface irrigation studies, residual soil NO_3 was less with reflectance-based N than with soil-test N ($P < 0.05$). The deepest depth sampled, 150 to 180 cm, had low levels of NO_3.

Overhead Sprinkler-Irrigation in 2015

Pre-fertilization soil NO_3–N in the soil-test-based N plots was 71 kg NO_3–N ha^{-1} in the 0- to 90-cm profile (Table 7; Fig. 1B). Soil-test-based N applications were 131 kg N ha^{-1}.

The NDVIA in the two reflectance-based treatments did not fall below their respective references during the growing season ($P > 0.05$, Fig. 3B). Therefore, the two NDVI-based N treatments were not adjusted upward. The NDVIA with zero-N did not drop significantly ($P < 0.05$) below the N-fertilized treatments until the 210th day of the year (28 July) or peak bloom. This was 3 wk after the third split of N fertilizer.

Biomass at first open boll averaged 10.0 Mg ha^{-1} in N-fertilized plots, and 8.6 Mg ha^{-1} in zero-N plots ($P < 0.05$, Table 7). Nitrogen uptake at first open boll ranged from 162 to 220 kg N ha^{-1} in N-fertilized plots and was 130 kg N ha^{-1} in zero-N plots ($P < 0.05$, Table 7). Net N mineralization was estimated at 63 kg N ha^{-1}, (130 kg N ha^{-1} N uptake– 20 kg NO_3–N ha^{-1} in irrigation- 47 kg NO_3–N ha^{-1} in 0- to 90-cm soil in the zero-N plots (Table 6). Recovery efficiency of added N fertilizer was greater than in the 2014 sprinkler irrigation study ($P < 0.05$). It should be pointed out that the 2014 study had lower N fertilizer application rates than in 2015, i.e., higher RE would be expected. The greatest RE in 2015 of 81% was with the low N rate of 59 kg N ha^{-1} (Table 7). The lowest RE of 41% was with the 1.3 × soil-test rate (170 kg N ha^{-1}).

Lint yields were lower ($P < 0.05$) for zero-N plots vs. the average of the N-fertilized plots (1984 and 2033 kg ha^{-1}, for whole plot, and 6-m yield samples, respectively [$P < 0.05$, Table 7]). There was no statistical differences among the N-fertilized plots ($P > 0.05$) for the 6-m sampling. Lint yield data with the yield monitor on the whole plot showed a lower SE than the 6-m by 2 row harvest areas. In 2015, yield monitor data showed statistically depressed lint yields with the reflectance-based treatments compared to the soil-test and 1.3 × soil-test treatments ($P < 0.05$, Table 7). Agrotain Plus with UAN showed statistical differences ($P < 0.05$) among the reflectance treatments, i.e., a lint yield depression with 59 kg N ha^{-1} and a lint yield increase at the 76 kg N ha^{-1} rate.

Deep percolation for sprinkler irrigation in 2015 was again estimated to be negligible, similar to 2014. However, similar to the surface irrigation study, after 2 yr, lower concentrations of soil NO_3–N were observed in the 120- to 150- and 150- to 180-cm layers than in the upper profile (Fig. 1B). Treatment trends in residual soil profile NO_3 after harvest in 2015 were similar to the year before ($P > 0.05$), with substantial build-up in the 1.3 × soil-test treatment (Fig. 1B; Table 6).

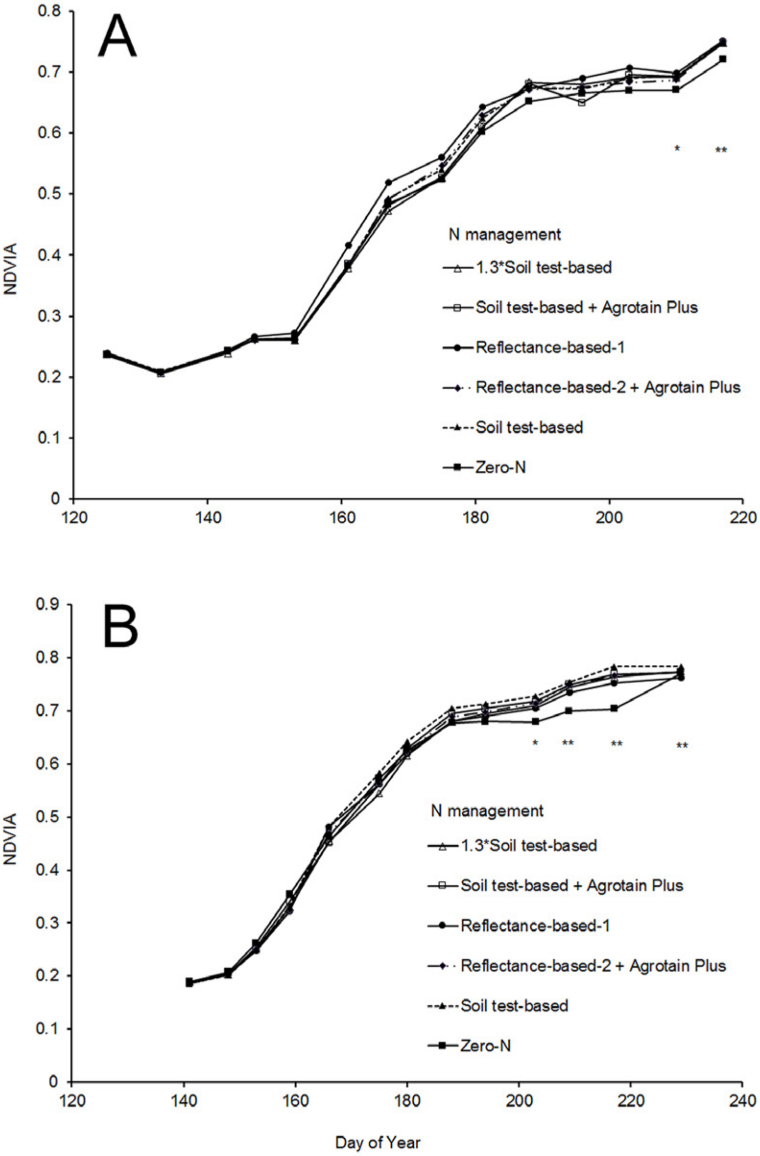

Fig. 3. Normalized difference vegetation index-amber (NDVIA) as affected by N-fertilizer management in overhead sprinkler-irrigated cotton, Maricopa, AZ; (A) 2014, and (B) 2015 (* and ** indicate N-fertilized plots are significantly less than zero-N plots at $P < 0.05$ and $P < 0.01$, respectively).

DISCUSSION

Lint and seed yield response to N fertilizer above zero-N controls was consistent in the four site-years of this study. However, similar to the work of Chua et al. (2003) and Bronson et al. (2011), there were few differences among N fertilizer treatments. The one instance of a yield depression was with reflectance-based-1 N management vs. the soil-test approach occurred under the overhead sprinkler in 2015 and was only 105 kg lint ha^{-1}. There was also a 158 kg lint ha^{-1} reduction with the reflectance-based-2 treatment compared to the 1.3 × soil-test treatment that same site-year.

Total N uptake at first open boll in these studies was on the higher end of the range for irrigation cotton studies worldwide (Bassett et al., 1970; Mullins and Burmester, 1990; Hunt et al., 1998; Norton and Silvertooth, 2007; Rochester, 2007; Janat, 2008; Bronson et al., 2011; Devkota et al., 2013). Maximum N uptake was >200 kg N ha^{-1} in both years under the sprinkler and >175 kg N ha^{-1} with surface irrigation. This trend is in part explained with the 200 and 225 kg N ha^{-1} N requirement of fertilizer, 0- to 90-cm depth soil NO_3 and irrigation water NO_3 for surface and sprinkler irrigations, respectively. Nitrogen uptake in the zero-N plots was similar among the four site-years ($P > 0.05$), ranging from 122 to 146 kg N ha^{-1}, and similar to that reported for subsurface drip irrigation in Texas (Yabaji et al., 2009; Bronson et al., 2011). However, large cotton plants with high N uptake do not always translate to high lint and seed yields, as fruit retention can be low in desert environments (Norton and Silvertooth, 2007).

Recovery efficiency of N in these studies had a wide range. On the low end, RE values for the surface irrigation in 2012 and 2013 were similar to the 25 to 35% reported at this site for cotton by Norton and Silvertooth (2007). It was expected that RE would be greater with overhead sprinkler irrigation than with surface irrigation. However, comparing REs between years and irrigation systems is difficult, as the N rates changed, and the number of splits of the N applications was two in the surface irrigation and three under the sprinkler. There is no statistical test to compare RE or other measures between the surface- and overhead-sprinkler irrigation studies. Very high RE values of 97 to 98% were observed with the reflectance-1 and reflectance-2 with Agrotain Plus in 2015 under the sprinkler. These remarkable RE values are comparable to the 94 to 101% reported by Bronson et al. (2011) with subsurface drip irrigation in Texas. The difference method of calculating RE assumes that soil N uptake by fertilized plants is the same as in zero-N plots. This assumption is often not the case, for example, fertilized plant roots explore deeper than zero-N plants. This can result in elevated RE estimates with the difference method compared to ^{15}N methods (Chua et al., 2003; Norton and Silvertooth, 2007).

Lint and seed yields, N uptake, and residual soil NO_3 were similar with either knifing of N or fertigation of N in the 2012 to 2013 surface-irrigation study. We are not aware of any other N

Table 7. Lint yield, seed yield, seed N uptake, internal and agronomic N use efficiency, biomass, N uptake, and N recovery efficiency as affected by N management in overhead sprinkler-irrigated cotton, Maricopa, AZ, in 2014 to 2015.

Nitrogen treatment	Fertilizer source†	Fertilizer rate	Lint yield–292 m^2	Lint yield–96 m^2	Seed yield	Seed N uptake	Internal N use efficiency	Agronomic N use efficiency	Biomass	Total N uptake	N Recovery efficiency
		kg N ha^{-1}	——— kg ha^{-1}		———	kg N ha^{-1}	— kg lint kg N^{-1}	—	Mg ha^{-1}	kg N ha^{-1}	%
				2014							
Zero-N		0	1694	1725	2156	82	12.5	–‡	8.4	146	–
Soil test-based N	UAN	179	1856	1693	2152	92	8.3	–	9.3	206	34
1.3×Soil test-based N	UAN	233	1827	1790	2324	98	8.6	–	9.0	202	24
Soil test-based N	UAN with Agrotain Plus	179	1884	1915	2486	102	10.1	–	8.8	189	24
Reflectance-based N-1	UAN	90	1880	1913	2427	100	9.9	–	9.5	195	55
Reflectance-based N-2	UAN	116	1820	1790	2300	93	9.4	–	9.0	193	40
Reflectance-based N-1	UAN with Agrotain Plus	90	1838	1836	2392	97	9.8	–	9.6	190	50
Reflectance-based N-2	UAN with Agrotain Plus	116	1789	1792	2243	91	9.9	–	8.8	183	32
Standard error			40	142	185	8	0.8	–	0.7	16	14
				Single degree of freedom contrasts							
UAN vs. UAN with Agrotain Plus			NS§	NS	NS	NS	NS	–	NS	NS	NS
Reflectance-based N-1. vs. soil test			NS	NS	NS	NS	*	–	NS	NS	NS
N-fertilized vs. zero-N			**	NS	NS	*	**	–	NS	**	–
				2015							
Zero-N		0	1632	1759	2552	87	14.3	–	8.6	130	–
Soil test-based N	UAN	131	2038	1985	3129	125	9.1	1.7	10.5	220	69
1.3×Soil test-based N	UAN	170	2048	2090	3265	113	10.5	2.0	9.7	200	41
Soil test-based N	UAN with Agrotain Plus	131	2097	2184	3360	130	11.9	3.2	9.4	187	43
Reflectance-based N-1	UAN	66	1933	1991	2956	110	10.2	3.4	10.3	195	97
Reflectance-based N-2	UAN	85	1889	1937	2955	114	9.9	2.1	10.2	199	81
Reflectance-based N-1	UAN with Agrotain Plus	66	1837	2088	3115	114	13.1	5.0	9.4	164	56
Reflectance-based N-2	UAN with Agrotain Plus	85	2044	1958	2994	114	9.3	2.3	10.4	213	98
Standard error			42	164	242	12	0.5	1.9	0.5	10	11
				Single degree of freedom contrasts							
UAN vs. UAN with Agrotain Plus			**	NS	NS	NS	NS	NS	NS	*	*
Reflectance-based N-1 vs. soil test			**	NS	NS	NS	NS	NS	NS	NS	**
N-fertilized vs. zero-N			**	*	**	**	**	–	**	**	–

* Significant at $P < 0.05$; ** significant at $P < 0.01$.

† UAN, urea ammonium nitrate; AS, ammonium sulfate.

‡ (–) indicates value could not be calculated.

§ NS, no significance at $P < 0.05$.

fertilizer management studies with cotton where N was fertigated. Jaynes et al. (1992), for a wheat study in Maricopa, reported significant deep leaching of N with fertigation at this site. In terms of farmers' practices, fertigation is usually more convenient, probably uses less energy than ground applications, and can be extended further into the long bloom period of desert cotton production, where tall plants preclude ground applicators from being used.

The use of DCD and NBPT addition to UAN compared to UAN alone, like many previous studies, showed no yield benefit (Kawakami et al., 2012; Watts et al., 2014), similar to the null effect with other EFFs (Freney et al., 1993; Rochester et al., 1996; Reeves and Touchton, 1989). There was a yield and N uptake reduction with Agrotain Plus under the sprinkler in 2015 (Table 7). The reason for this is not clear. Ammonia loss was probably not a factor under the sprinkler, as UAN was watered-in immediately, and the Trix soil has high cation exchange capacity which retains NH_4. Bronson et al. (1989) reported that the nitrification inhibitor in Agrotain Plus, DCD, breaks down quickly with soil temperatures >22°C, which would limit its effectiveness in the desert.

It is clear from these results that the soil-test based N algorithm tested here is prescribing too much N fertilizer. This conclusion is based on the statistically similar yields of the reflectance N rates of 50% less than the soil test treatments. Additionally, residual soil profile NO_3 accumulated in the soil-test treatments, an important indicator of over-fertilizing (McConnell et al., 1996; Bronson et al., 2001). The critical missing factor in the soil-test approach is probably not accounting for net N mineralization, which ranged from 51 to 105 kg N ha^{-1}. Vegetation indices derived from canopy reflectance should theoretically reflect N mineralization, with higher VIs in zero-N plots as net N mineralization increase. In contrast to the apparent over-fertilization with the soil-test algorithm, the results of these studies in Arizona demonstrate the strong potential of in-season reflectance-based N management, first applied in Texas (Bronson et al., 2011) to provide a more optimum N recommendation to irrigated cotton in arid environments.

The different deep percolation estimates for the two irrigation systems in this study imply more efficient irrigation of cotton with the overhead sprinkler system, since no deep percolation was calculated by the water balance. The deep percolation estimated for the surface irrigation (4–11% of total water applied) was less than the 18% of irrigation (or 16% of total water applied) reported at this site by Rice et al. (1986) for a bare soil that was flood irrigated. The 3.2 cm of deep percolation estimated in 2013 compares well with the 2.8 to 2.9 cm estimates by Hunsaker et al. (2015) in a surface-irrigation cotton study in Maricopa, AZ, which also used a 45% soil water depletion. Dedrick (1984) evaluated surface-irrigation systems used for cotton in the desert Southwest and determined the expected seasonal irrigation efficiency in the range of 75 to 90% for graded furrow systems.

We cannot make strong conclusions from the soil profile NO_3 data after harvest about NO_3 leaching. The initial study in 2013 had very high spring NO_3 levels from 150 to 180 cm (Fig. 1). When these levels declined by December, it is not clear if the pathway was leaching or plant N uptake. In the first month or so of the season, the rooting zone was probably shallow and leaching of initial NO_3 was more likely. We can surmise from the differences in the deep percolation estimates from the water balances that NO_3 leaching was the main N loss pathway in the surface irrigation studies from 2012 to 2103. However, a modest accumulation of NO_3–N in the 150- to 180-cm soil layer under the sprinkler after 2 yr of study suggests that some leaching may have occurred, contrary to the water balance result. We can probably safely assume that the root zone in the overhead-sprinkler study was shallower than in the surface-irrigated field, due to the frequent, lighter irrigations. Hutmacher et al. (2004) measured root weights in soil profile samples, and reported in surface-irrigated cotton in California that only 6% roots were below 1.2 m.

In summary, these studies demonstrate the value of managing in-season N fertilizer to surface- and overhead sprinkler with weekly canopy reflectance for cotton in the high production system of the desert Southwest. Nitrogen recovery was variable, but it was clearly demonstrated what the maximum N uptake efficiency can be. The results of these four site-years can be extrapolated well beyond Arizona to many of the high yielding, arid irrigated cotton producing arid and semiarid areas of the world. Finally, our results indicate that better methods to quantify NO_3 leaching on these large-scale field studies are needed.

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